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FINAL REPORT  
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Contract No. F61708-96-W0229.  
THEORETICAL AND EXPERIMENTAL ACHIEVEMENTS  
IN THE FIELD OF INDUCED GAMMA EMISSION

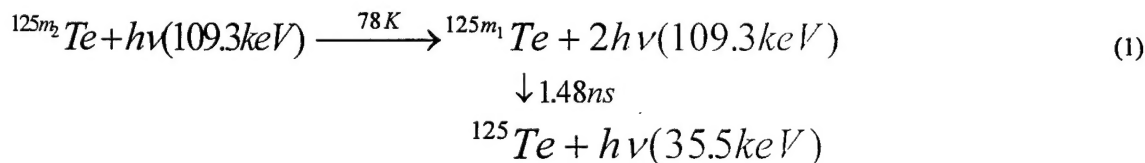
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Abstract

A critical analysis is presented for all published to date experimental data concerning the induced gamma-emission (*IGE*) in processes  $^{125m2}\text{Te}(\gamma, 2\gamma)^{125m1}\text{Te}$ ,  $^{123m2}\text{Te}(\gamma, 2\gamma)^{123m1}\text{Te}$ , and  $^{119m2}\text{Sn}(\gamma, 2\gamma)^{119m1}\text{Sn}$ . The co-operative model of the *IGE* phenomenon is deduced from quantum electrodynamics.

Experimental results

In 1984 we published<sup>1</sup> a results of experimental study regarding the *IGE* process:



In Ref.<sup>1</sup> the experimental effect is taken as:

$$\varepsilon = \frac{\Delta\Phi}{\Phi}, \quad (2)$$

where  $\Delta\Phi$  is the number of gamma-quanta emitted by stimulation at the  $\text{Be}^{125m2}\text{Te}$  sample temperature  $T_{\text{exp}}=78\text{K}$ , and  $\Phi$  is the number of gamma-quanta spontaneously emitted at sample temperature  $300\text{K}$ . The value  $\varepsilon_{\text{exp}} = 1.2 \pm 0.6\%$  had been obtained in Ref. <sup>1</sup>. In order to exclude the contribution in  $\varepsilon_{\text{exp}}$  from a temperature rise of sample density we had reproduced the *IGE* process (1) in Ref.<sup>2</sup>. In the latter work the experimental effect is taken as:

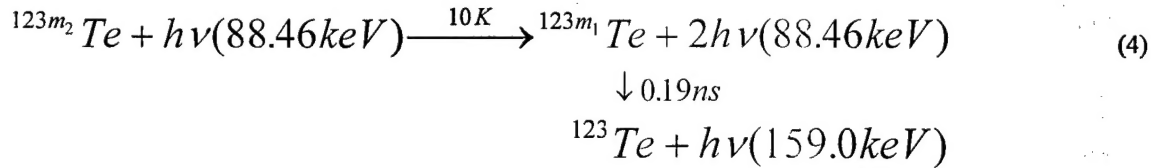
$$\varepsilon_{\text{exp}} = \frac{\Phi_{2\gamma}}{\Phi}, \quad (3)$$

where  $\Phi_{2\gamma}$  is a number of coherent pairs  $2h\nu(109.3\text{keV})$  originated in the process (1).

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Finally, in Ref.<sup>3</sup> we had reproduced the *IGE* process (1) using both techniques (2) and (3) for  $\varepsilon_{\text{exp}}$ . The resulting experimental data are presented in Table 1.

Taken together References [1-3] demonstrate with confidence a reality of the *IGE* process (1). Nevertheless, by the early 1990s there was some uncertainty as to the mechanism of the *IGE* process. Hence, we undertook the experimental study regarding the *IGE* process<sup>3</sup>:



The obtained value of  $\varepsilon_{\text{exp}}$  for process (4) together with data for reaction (1) had demonstrated<sup>3-5</sup> that realized *IGE* process is a collective polynuclear superradiance rather than stimulated emission of Mössbauer radiation. The corresponding theoretical equation for the effect value can be written as<sup>3-5</sup>:

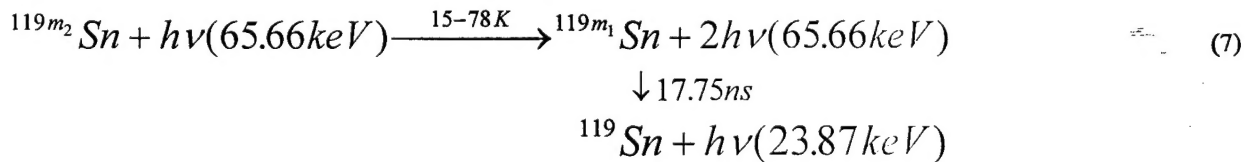
$$\varepsilon_{\text{theor}} = \frac{2\pi N_x f_m \beta \tau_{\text{down}}}{3\mu^3 (1 + \alpha)(\tau_{\text{up}} + \tau_{\text{down}})}, \quad (5)$$

where  $N_x$  is a number of inversion,  $f_m$  is the Mössbauer factor,  $\beta$  is a branching factor,  $\mu$  is the linear losses coefficient,  $\alpha$  is an internal conversion factor,  $\tau_{\text{up}}$  is the upper level life time, and  $\tau_{\text{down}}$  is the lower level life time. Eqn. (5) holds<sup>5</sup> only when the lattice temperature ( $T_{\text{exp}}$ ) is decreased to the value  $T_\Lambda$  wherein a de Broglie thermal wavelength for nucleus  $^*X$  exceeds the gamma-quantum wavelength ( $\Lambda$ ):

$$T_{\text{exp}} \leq T_\Lambda = \frac{(\hbar / \Lambda)^2}{2km_x}. \quad (6)$$

Here  $\hbar$  is the Planck constant,  $k$  is the Boltzmann constant, and  $m_x$  is a mass for the  $^*X$  nucleus. The relationship  $N_x = [^*X]$  was true in conditions of our experiments<sup>1-5</sup>. One should recognize from the data of Table 1 that Eqn. (5) of co-operative model describes within the error limits all the experimental results obtained in Ref.<sup>1-5</sup>.

In Table 1 we present also the results of experimental study of the process (4) in ref.<sup>6</sup> and process



in Refs.<sup>6,7</sup>.

Table 1. Comparison of theoretically calculated by formula (5) and experimentally measured ratio  $\varepsilon = \Delta\Phi_\gamma / \Phi_\gamma$ , where  $\Delta\Phi_\gamma$  is the number of gamma-quanta emitted by stimulation at matrix temperature  $T_{\text{exp}}$ , and  $\Phi_\gamma$  is the number of gamma-quanta emitted spontaneously at matrix temperature 300K.

nuclide (*X)	$^{125\text{m}2}\text{Te}$		$^{123\text{m}2}\text{Te}$		$^{119\text{m}2}\text{Sn}$	
	<i>BeTe</i>		<i>Mg<sub>3</sub>TeO<sub>6</sub></i>	<i>Mg<sub>3</sub>TeO<sub>6</sub> + MgO</i>	<i>SnO</i>	<i>SnO<sub>2</sub></i>
$T_\lambda / K$	10		6.6	6.6	3.6	3.6
Debye temperature / K	390		350	375	154	160
$[*X] / 10^{18} \text{ atoms}\cdot\text{cm}^{-3}$	12±5	4.9±1.5	34±7	1.0±0.2	5±1	9±3
$T_{\text{exp}} / K$	78	10	10	78	15	78
Mössbauer factor $f_m(T_{\text{exp}})$	0.10±0.02	0.108	0.18±0.01	0.13	0.0214	0.01
$\mu_0^{-1} / \text{cm}$	0.2062	0.2062	0.1639	0.33	0.0293	0.032
$(4\pi/3)[*X]\mu_0^{-3} / 10^{16} \text{ atoms}$	44±18	18±6	63±13	16±5	0.053±0.011	0.12
$\frac{10^{20} f_m \tau_d}{2(1 + \alpha_{up})(\tau_{up} + \tau_d)}$	4.03	4.35	0.148	0.103	0.0126	0.0059
$\varepsilon_{\text{theor}} / \%$	1.8±0.7	0.8±0.3	0.09±0.02	0.02±0.01	$7.8 \cdot 10^{-6}$	$7 \cdot 10^{-6}$
$\varepsilon_{\text{exp}} / \%$	1.2±0.6	0.35±0.15	0.05±0.03	0.30±0.06	≤0.0012	0.02± ±0.01
reference for $\varepsilon_{\text{exp}}$	Skor, Dz <sup>1</sup> , 1984	Skor, Dz <sup>3</sup> , 1995	Skor, Dz <sup>3</sup> , 1995	Bond, Dz <sup>6</sup> , 1996	ITEPH <sup>7</sup> , 1989	Bond, Dz <sup>6</sup> 1996

### Co-operative effects in stimulated emission

If we use a long-lived isomer both as storage and lasing level, the stimulated emission cross section is very small because of the very weak coupling between the gamma-radiation and the nuclei. Nevertheless, if the nuclei are imbedded in a lattice, co-operative effects in the stimulated emission could enhance the amplification and thus the gain substantially.

Consider an incoming gamma-radiation with a resonant (or near-resonant) frequency. That radiation interacts with all the nuclei in the ensemble and can stimulate those nuclei which are in the excited state to emit a photon. The probability for such a process can be written as<sup>8</sup>:

$$P_{stim.em.}(\hat{k}\sigma, t) = \left| \left\langle n_{\hat{k}\sigma} + 1, \Psi_F(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) \left| \vec{J}(\vec{r}) \cdot \vec{A}_{\hat{k}\sigma}(\vec{r}, t) \right| n_{\hat{k}\sigma}, \Psi_I(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) \right\rangle \right|^2, \quad (2-1)$$

where  $\vec{A}_{\hat{k}\sigma}(\vec{r}, t)$  is the field at point  $\vec{r}$  associated to the stimulating radiation with momentum  $\hat{k}$  and helicity  $\sigma$ . For an incoming plane wave the vector potential is<sup>9</sup>:

$$\vec{A}_{\hat{k}\sigma}(\vec{r}, t) = \vec{A}_{\hat{k}\sigma}^* e^{-i(\vec{k}\vec{r} - \omega t)} + \vec{A}_{\hat{k}\sigma} e^{i(\vec{k}\vec{r} - \omega t)}, \quad (2-2)$$

in which  $\vec{A}_{\hat{k}\sigma}^*$  and  $\vec{A}_{\hat{k}\sigma}$  are respectively related to the photon creation operator  $a_{\hat{k}\sigma}^+$  and the destruction operator  $a_{\hat{k}\sigma}$ . Since we consider only stimulated emission we can write:

$$\vec{A}_{\hat{k}\sigma}(\vec{r}, t) = a_{\hat{k}\sigma}^+ \vec{A}_{\hat{k}\sigma}(\vec{r}, t). \quad (2-3)$$

The total nuclear current operator  $\vec{J}(\vec{r})$  can be written as a sum of currents  $\vec{j}_l(\vec{r})$  each belonging to one single nucleus. The position vector  $\vec{r}$  can for each nucleus be written as a function of the position of the nuclear mass center  $\vec{r}_l$  and a charge distribution vector  $\vec{\rho}_l$ . Then:

$$\vec{J}(\vec{r}) = \sum_l \vec{j}_l(\vec{r}) = \sum_l \vec{j}_l(\vec{r}_l + \vec{\rho}_l). \quad (2-4)$$

The wave functions of the initial and final state are products of single nucleus wave functions:

$$\begin{aligned} \Psi_I(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) &= \prod_l \int_{|\Delta\vec{r}_l|} \varphi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) f(\vec{\xi}) d\vec{\xi} = \\ &= \int \prod_l \varphi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) f(\vec{\xi}) d\vec{\xi}, \end{aligned} \quad (2-5)$$

$$\Psi_F(\vec{r}_1, \vec{r}_2, \dots, \vec{r}_n, \vec{r}) = \int \prod_j \Phi_j(\vec{r}_j + \vec{\xi} + \vec{\rho}_j) f(\vec{\xi}) d\vec{\xi}. \quad (2-6)$$

Here the  $f(\vec{\xi})$  function presents a Heisenberg uncertainty for the spatial coordinate  $\vec{r}$ .

As we consider only stimulated emission, we can restrict the initial state to all nuclei which are in the excited state. The total transition amplitude is then reduced to a sum of single nucleus matrix elements. Then, for every  $l$  in the absence of any temperature gradient in a lattice following relationship is true as result of the Heisenberg uncertainty relation:

$$|\Delta \vec{r}_l| = |\Delta \vec{r}| = \sqrt{\frac{2\pi\hbar^2}{m_X k T_{lat}}}, \quad (2-7)$$

where  $\hbar$  is the Planck constant,  $k$  is the Boltzman constant,  $m_X$  is a mass of radiating nucleus.  $T_{lat}$  is a lattice temperature. Now instead equation (28) of Ref.<sup>8</sup> we obtain following equation for total transition amplitude:

$$\chi_{tot}(\hat{k}\sigma, t) = \sum_l \int_{|\Delta \vec{r}|} \langle \Phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) | \vec{j}_l(\vec{r}_l + \vec{\rho}_l) \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}_l) | \varphi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) \rangle f(\vec{\xi}) d\vec{\xi}. \quad (2-8)$$

Under condition  $f(\vec{\xi}) = \delta(\vec{\xi})$  our equations (2-5), (2-6), (2-8) coincides with equations (26), (27), (28) of Ref.<sup>8</sup>. Instead of equation (29) in Ref.<sup>8</sup> the total transition amplitude becomes equal:

$$\begin{aligned} \chi_{tot}(\hat{k}\sigma, t) &= \int_{|\Delta \vec{r}|} \sum_l \langle \Phi(\vec{\rho} + \vec{\xi}) | \vec{j}(\vec{\rho}) \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}, t) T(-\vec{r}_l) | \varphi(\vec{\rho} + \vec{\xi}) \rangle f(\vec{\xi}) d\vec{\xi} = \\ &= \sum_l \left\langle \Phi(\vec{\rho}) | \vec{j}(\vec{\rho}) \cdot \int_{|\Delta \vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r} + \vec{\rho}, t) T(-\vec{r}_l - \vec{\xi}) f(\vec{\xi}) d\vec{\xi} | \varphi(\vec{\rho}) \right\rangle, \end{aligned} \quad (2-9)$$

where:

$$\int_{|\Delta \vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}, t) T(-\vec{r}_l - \vec{\xi}) f(\vec{\xi}) d\vec{\xi} = \vec{A}_{\hat{k}\sigma}(\rho, t) \int_{|\Delta \vec{r}|} e^{-2i\vec{k}(\vec{r}_l + \vec{\xi})} f(\vec{\xi}) d\vec{\xi}. \quad (2-10)$$

The total transition probability for stimulated emission can thus be written as:

$$P_{stim.em.}(\hat{k}\sigma, T_{lat}, t) = |\dots|^2 \sum_{j,l} \int_{|\Delta \vec{r}|} e^{-2i\vec{k}(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi}) d\vec{\xi}, \quad (2-11)$$

where:

$$|\dots|^2 = \left| \langle \Phi(\vec{\rho}) | \vec{j}(\vec{\rho}) \cdot \vec{A}(\vec{\rho}, t) | \varphi(\vec{\rho}) \rangle \right|^2 = \hbar \omega_{res} A_{21} \frac{f_m(T_{lat}) \beta \hbar \Gamma_{up} \hbar \Gamma_{tot}}{4(1+\alpha) \left[ (E_{21} - \hbar \omega)^2 + \frac{1}{4} (\hbar \Gamma_{tot})^2 \right]}. \quad (2-12)$$

Here  $\beta$  is a branching factor,  $\alpha$  is an interval conversion factor,  $f_m$  is the Mössbauer factor,  $\Gamma_{up}$  is a line width of the upper level,  $\Gamma_{tot}$  is the total line width,  $A_{21}$  is the Einstein coefficient,  $\hbar \omega_{res} = E_{21}$  is the energy of electromagnetic transition.

Under condition  $|\Delta \vec{r}| \ll |\vec{k}|^{-1}$  there are both situations outlined by equations (32)-(36) of Ref. [8]. However, under opposite condition  $|\Delta \vec{r}| \geq |\vec{k}|^{-1}$  we get:

$$\sum_{j,l} \int_{|\Delta \vec{r}|} e^{-2i\vec{k}(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi}) d\vec{\xi} = \kappa(T_{lat}) \sum_{j,l} 1 = (N')^2 \kappa(T_{lat}), \quad (2-13)$$

where:

$$N = [N]l_x l_y l_z \quad (2-14)$$

$$l_j = \text{Min}(L_j, \mu_j^{-1}), \quad (2-15)$$

$$\kappa(T_{lat}) = \begin{cases} 1, & \text{if } T_{lat} \leq T_\Lambda \\ (T_\Lambda / T_{lat})^{0.5}, & \text{if } T_{lat} > T_\Lambda, \end{cases} \quad (2-16)$$

$$T_\Lambda = \frac{(\hbar / \Lambda_{21})^2}{2km_x}, \quad (2-17)$$

$L_j$  is the sample length along  $j$ -axis,  $\mu_j$  is the absorption coefficient along  $j$ -axis, and Eqn. (2-17) is the same as Eqn. (6). Now one might see that equations (2-11) - (2-17) under condition  $|\Delta \vec{r}| \geq |\vec{k}|^{-1}$  coincides completely with basic equation (5).

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\_\_\_\_\_, contract \_\_\_\_\_)

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